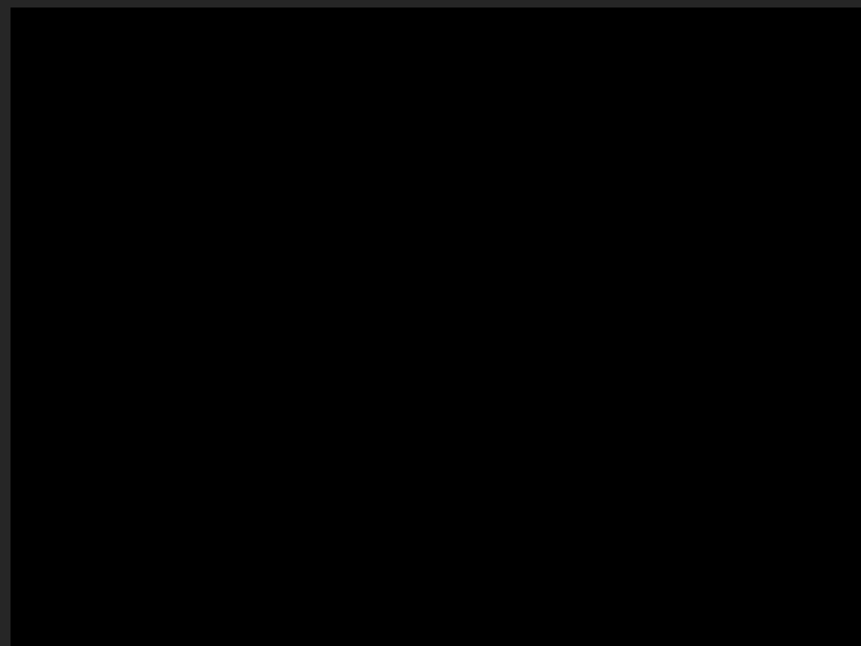
INTRODUCTION

TO

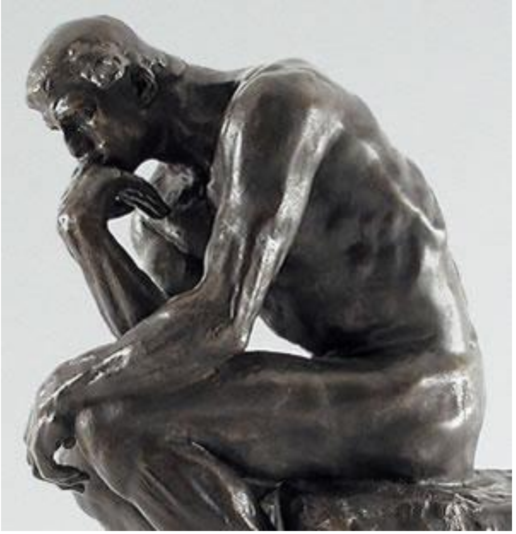
SYSTEMS ENGINEERING

Alberto Sols, Ph. D.

- Systems and systems engineering
- The systems life cycle
- The systems engineering process
- Stakeholders and their requirements
- **Design concepts**
- Functional analysis and system design
- Design reviews
- Integration, verification and validation
- Systems of systems



Design concepts



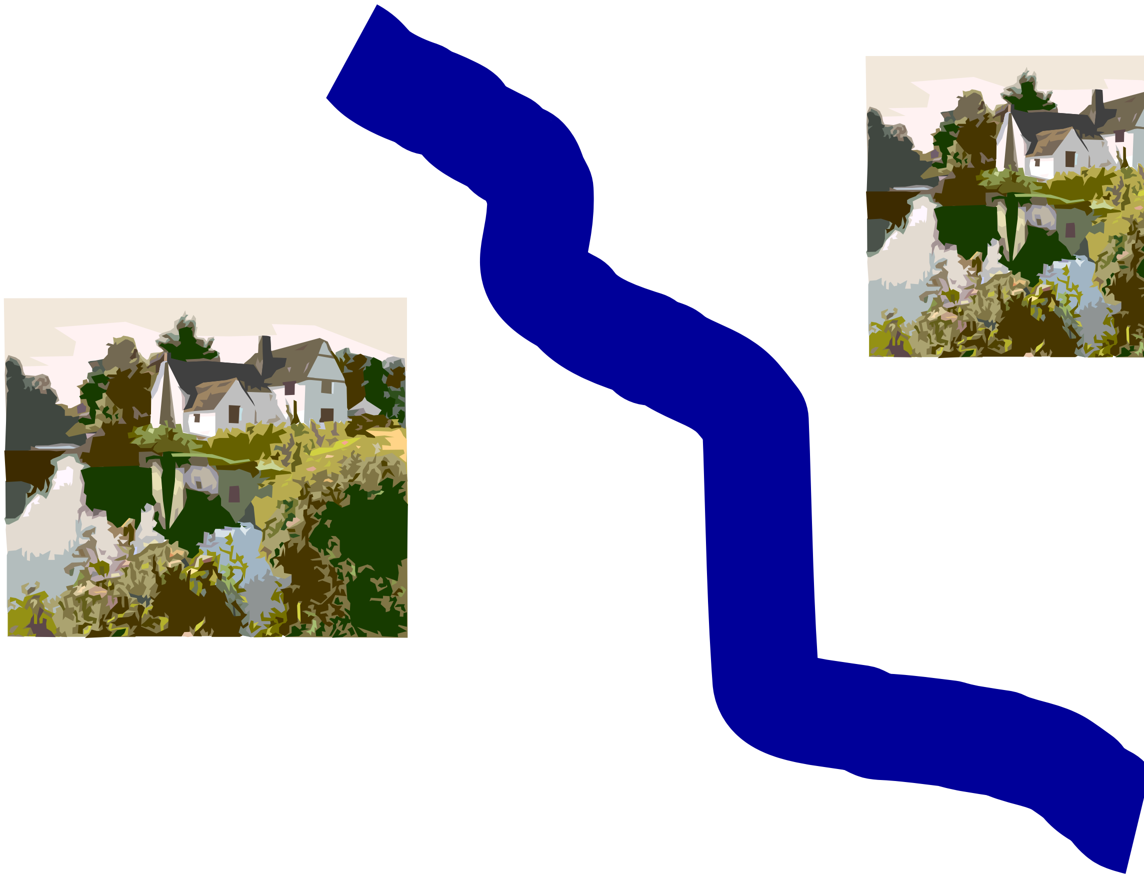
Design concepts are all potential systems or solutions to the identified need or market opportunity.

Design concepts

- Given a need or opportunity, the first step is to identify ALL potential systems or solutions (or as many as possible).

- Then, it will be necessary to discriminate those solutions worth exploring further, to eventually select the preferred one.

Example of perceived need

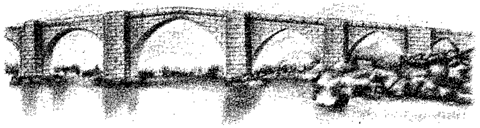


Let us consider two villages, separated by a river. Their inhabitants wished to be communicated and they hire a systems engineer ….

Example of perceived need

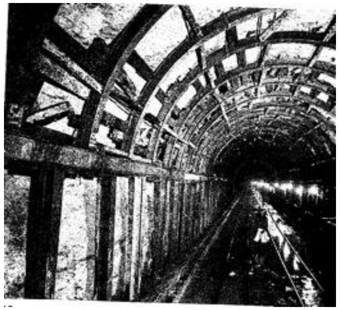
The systems engineer could easily think of a few potential solutions or design concepts:

Bridge



Ferry

Tunnel



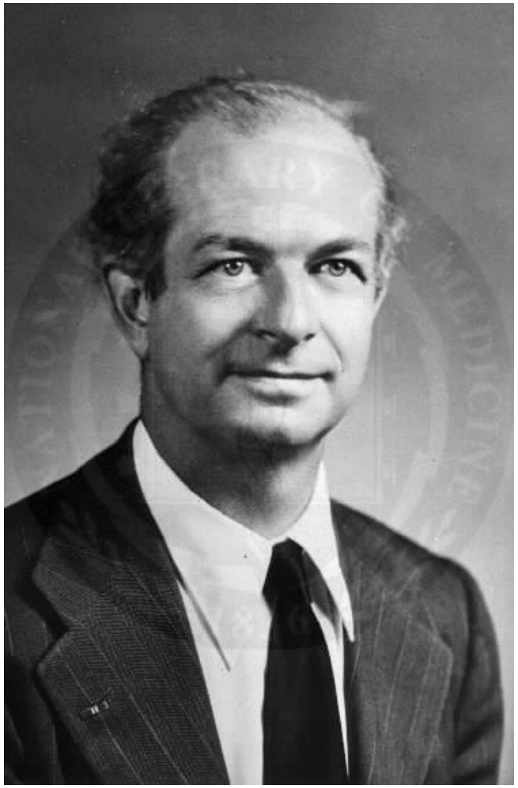
Example of perceived need

Although there could be other options:

air ballon

helicopter

rope challenge



To have good ideas, you need to have many ideas.

(Linus Pauling)

Example of perceived need

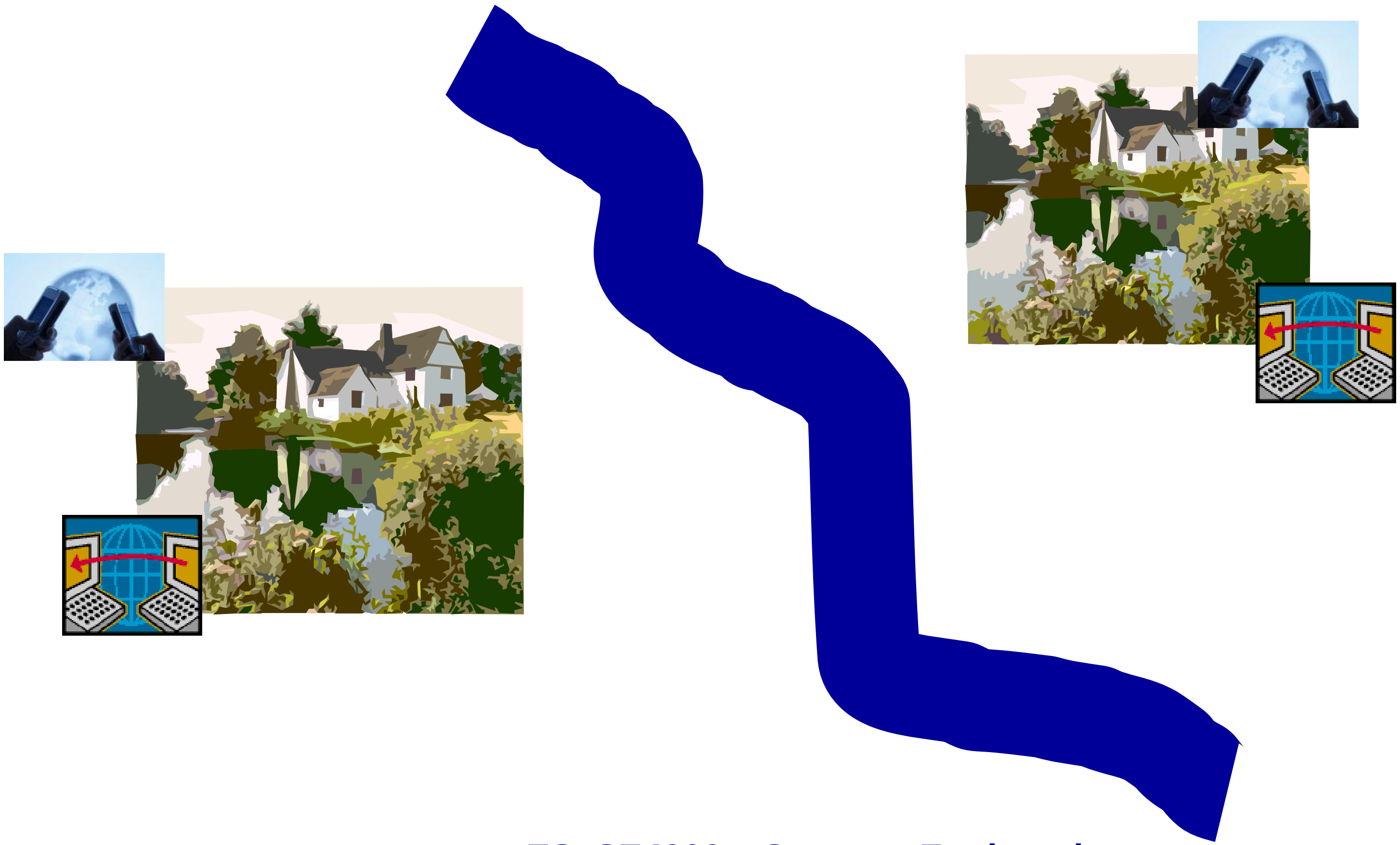
And still there could be more options:

Alter course of river

Relocate a village

Example of perceived need

But the very first step is to make sure the need or opportunity is really well understood. Perhaps what the people wanted was to be communicated via phone and/or e-mail!



Needs versus solutions

Need/Opportunity

Facilitate flow of people and materials

Potential solutions

Tunnel
Ballon
Bridge
Ferry
Alter course of river
Relocate village
Catapult
…..

What is essential is to differentiate the domain of the need or opportunity and the domain of potential solutions!

Requirements

In the considered example, we could have the following requirements:

High-level requirement: the inhabitants of the two villages are to be able to cross the river, including transport of personal cargo.

Detailed requirement (assuming selection of ferry as preferred design concept): the ferry is to have capacity for at least 250 people, all seated in a covered cabin.

Detailed requirement (assuming selection of tunnel as preferred design concept): the tunnel is to have one lane plus shoulder of standard widths, in each direction.

Preferred design concept

- Starting with the high-level system requirements, potential solutions or design concepts are identified. Those alternative design concepts are then evaluated with regards to the appropriate design criteria.
- A useful method is the Pugh matrix, or criteria-based matrix Qualitative evaluations are conducted for each identified concept and each considered criteria, in terms of relative degree of fulfillment.
- As with any other method, the ideal situation is to have a wide spectrum of design concepts and the array of criteria that reflects the aspects and characteristics deemed essential by the customer.

Pugh matrix

	Design concept alternatives				
Criteria	**1**	**2**	**3**	**4**	**5**
A					
B					
C					
D					
E					
F					
G					
H					
$\Sigma +$					
$\Sigma -$					
Σs					

"+" represents performance better than required

"-" represents performance lower than required

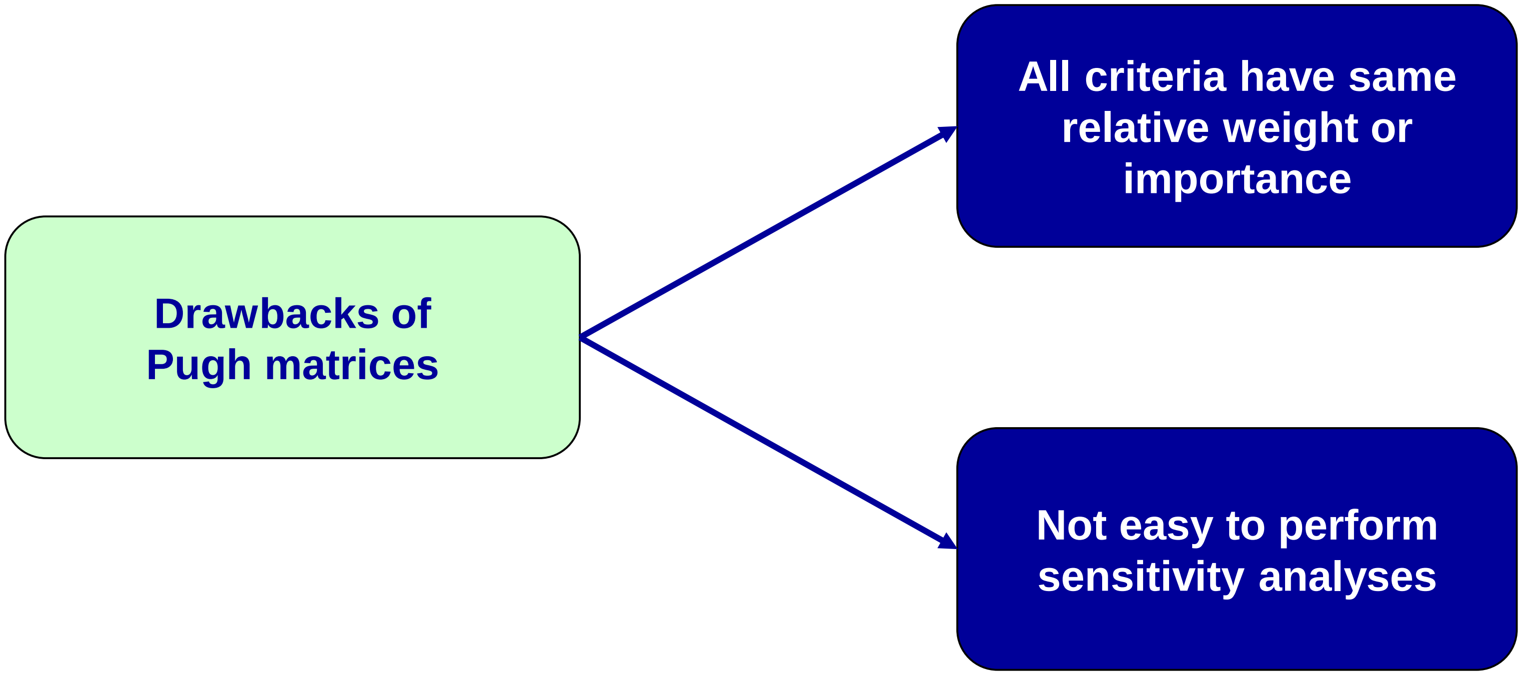
"s" represents performance as required

Pugh matrix

	Design concept alternatives				
Criteria		 2	 3	**4**	**5**
Initial cost	s	+	-		
Life-cycle cost	s	+	-		
All-weather cap.	+	-	s		
Capacity	+	-	s		
Useful life	+	-	s		
F					
G					
H					
$\Sigma +$	3	2	0		
$\Sigma -$	0	3	2		
Σs	2	0	3		

"+" represents performance better than required
"-" represents performance lower than required
"s" represents performance as required

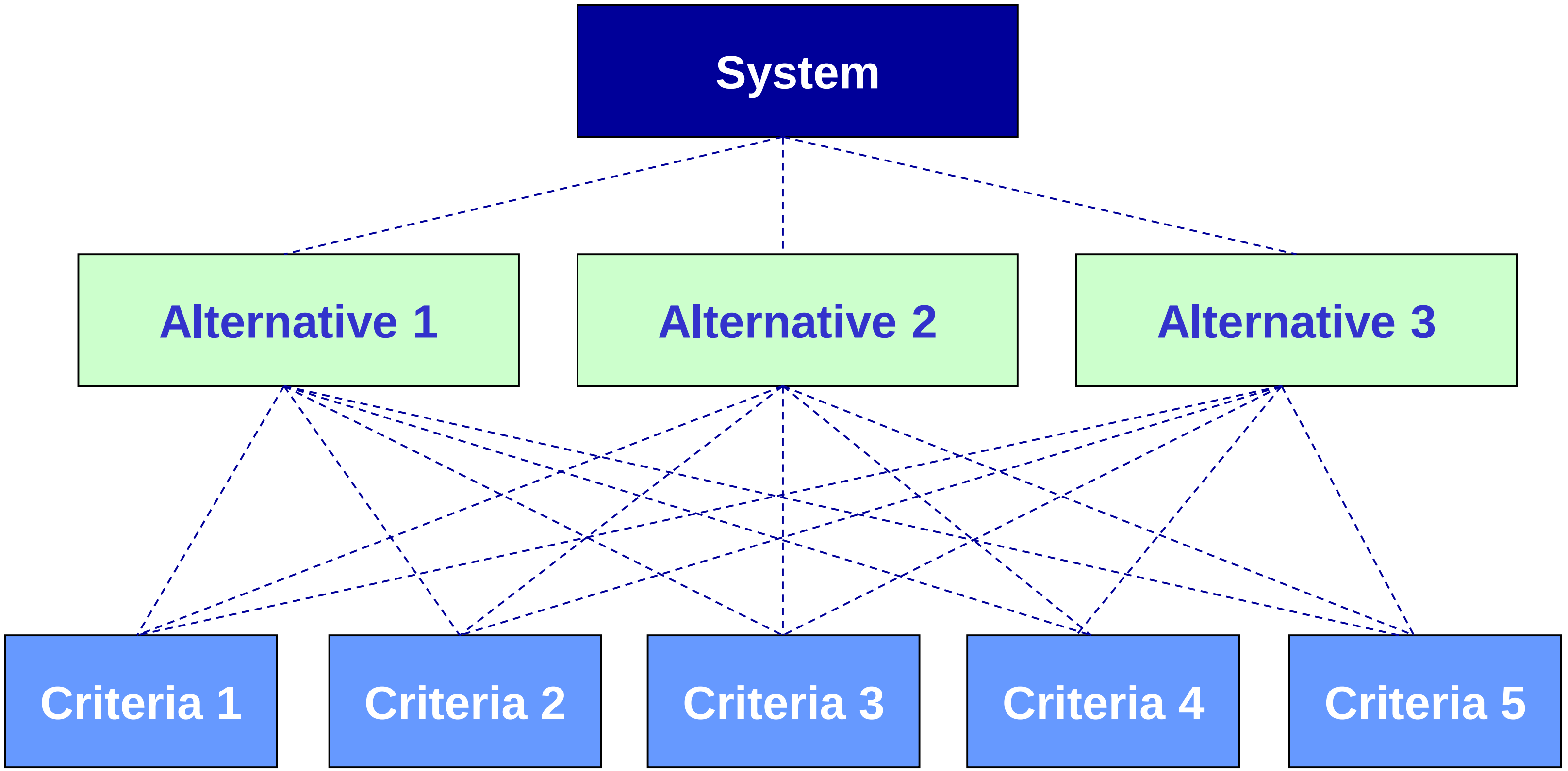
Pugh matrix

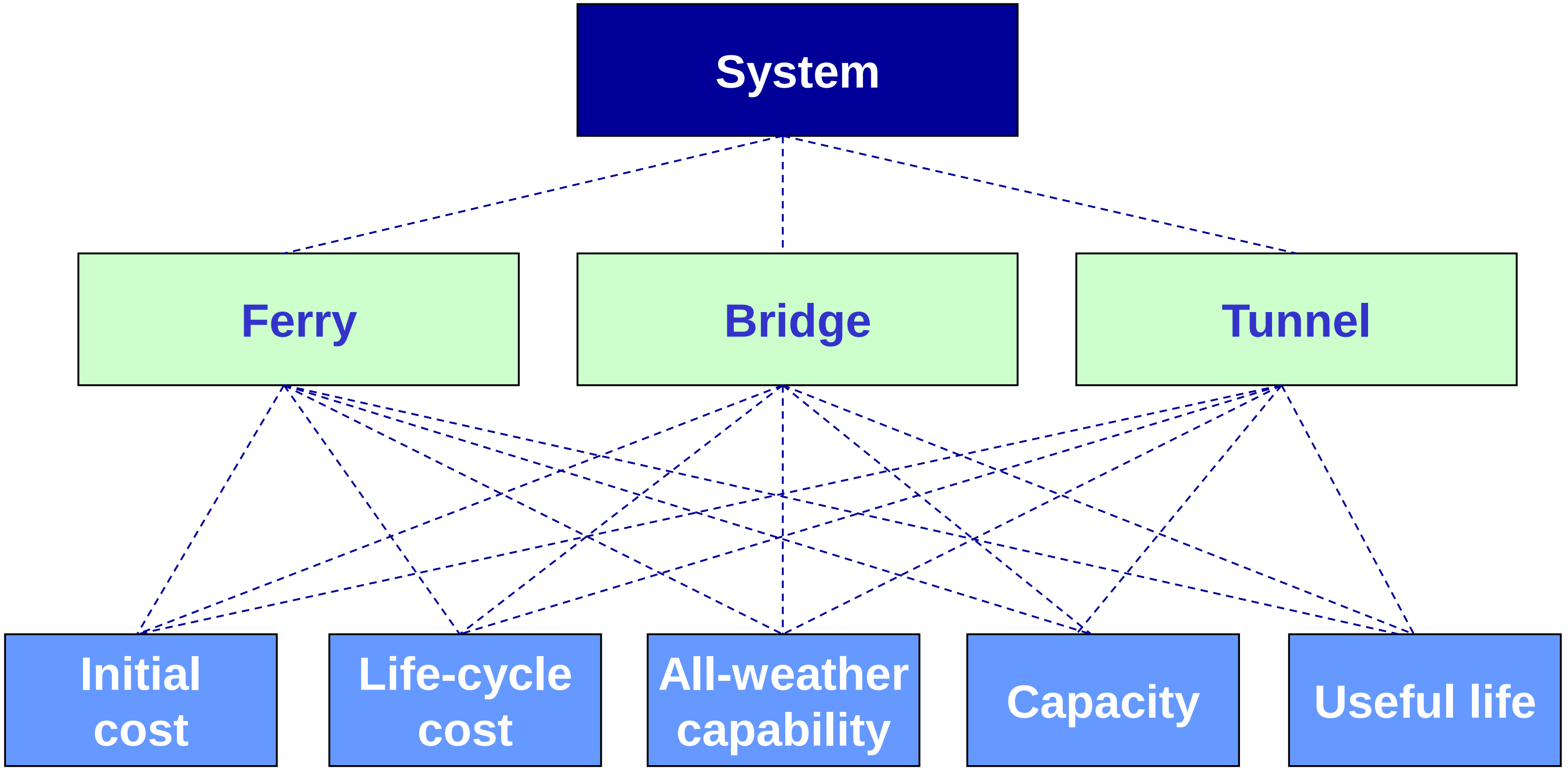

Drawbacks of
Pugh matrices
All criteria have same
relative weight or
importance
Not easy to perform
sensitivity analyses

- The Analytic Hierarchy Process (AHP) developed by Saaty allows the evaluation of alternatives with respect to several criteria, based on pair-wise comparisons.

- **The AHP method has the advantage that it explicits the process followed by the decision maker, allowing thus for discussions and exchange of interpretations; furthermore, it facilitates the performance of sensitivity analyses.**

- **Nevertheless, and in spite of it formal, mathematical appearance, there is a high degree of subjectivity embedded in the method, as the assignment of values in the pair-wise comparisons remains purely subjective.**


System
Alternative 1
Alternative 2
Alternative 3
Criteria 1
Criteria 2
Criteria 3
Criteria 4
Criteria 5



For the considered example, five criteria are deemed relevant in the selection of the preferred alternative or design concept.

Pair-wise comparisons are performed, first among criteria and later between alternatives, for each of the criteria.

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5
Criteria 1	1	3	1 / 7	7	1 / 9
Criteria 2	1 / 3	1	5	7	
Criteria 3	7	1 / 5	1		
Criteria 4	1 / 7	1 / 7		1	
Criteria 5	9				1

Criteria 1	Alternative 1	Alternative 2	Alternative 3
Alternative 1	1	1 / 3	1 / 7
Alternative 2	3	1	1 / 5
Alternative 3	7	5	1

1 equally preferred / important
3 slightly preferred / important
5 clearly preferred / important
7 strongly preferred / important
9 absolutely preferred / important

Pair-wise comparisons are performed, first among criteria and later between alternatives, for each of the criteria.

						Decimal equivalents				
	A	B	C	D	E	A	B	C	D	E
A. Acquisition cost	1	1 / 5	1 / 5	1 / 3	1 / 7	1,0000	0,2000	0,2000	0,3333	0,1429
B. Life cycle cost	5	1	1 / 3	1 / 3	3	5,0000	1,0000	0,3333	0,3333	3,0000
C. All-weather capability	5	3	1	9	3	5,0000	3,0000	1,0000	9,0000	3,0000
D. Capacity	3	3	1 / 9	1	3	3,0000	3,0000	0,1111	1,0000	3,0000
E. Useful life	7	1 / 3	1 / 3	1 / 3	1	7,0000	0,3333	0,3333	0,3333	1,0000
						21,0000	7,5333	1,9778	11,0000	10,1429

1+5+5+3+7 = 21

Divide the value with the number of the colonne
1/21 – 5/21 ..

Criteria weights are then normalized:

0,0476+0,0265+0,1011+0,0303+0,0141 = 0,2197

0,2197 / 5 = 0,0439

1 / 21 = 0,0476

		Normalized weights					Row	Average
		A	B	C	D	E		
A. Acquisition cost		0,0476	0,0265	0,1011	0,0303	0,0141	0,2197	0,0439
B. Life cycle cost		0,2381	0,1327	0,1685	0,0303	0,2958	0,8655	0,1731
C. All-weather capability		0,2381	0,3982	0,5056	0,8182	0,2958	2,2559	0,4512
D. Capacity		0,1429	0,3982	0,0562	0,0909	0,2958	0,9840	0,1968
E. Useful life		0,3333	0,0442	0,1685	0,0303	0,0986	0,6750	0,1350
		1,0000	1,0000	1,0000	1,0000	1,0000		1,0000

Comparison of design concepts with regards to initial cost:

INITIAL COST	Ferry	Bridge	Tunnel	Decimal equivalents Ferry	Decimal equivalents Bridge	Decimal equivalents Tunnel	Normalized weights Ferry	Normalized weights Bridge	Normalized weights Tunnel	Row	Average
Ferry	1	1 / 5	3	1,0000	0,2000	3,0000	0,1579	0,1489	0,2727	0,5796	0,1932
Bridge	5	1	7	5,0000	1,0000	7,0000	0,7895	0,7447	0,6364	2,1705	0,7235
Tunnel	1 / 3	1 / 7	1	0,3333	0,1429	1,0000	0,0526	0,1064	0,0909	0,2499	0,0833
				6,3333	1,3429	11,0000					1,0000

Høgskolen i Søraust-Noreg

Comparison of design concepts with regards to life-cycle cost:

LIFE CYCLE COST				Decimal equivalents			Normalized weights			Row	Average
	Ferry	Bridge	Tunnel	Ferry	Bridge	Tunnel	Ferry	Bridge	Tunnel		
Ferry	1	1 / 3	3	1,0000	0,3333	3,0000	0,2308	0,2174	0,3333	0,7815	0,2605
Bridge	3	1	5	3,0000	1,0000	5,0000	0,6923	0,6522	0,5556	1,9000	0,6333
Tunnel	1 / 3	1 / 5	1	0,3333	0,2000	1,0000	0,0769	0,1304	0,1111	0,3185	0,1062
				4,3333	1,5333	9,0000					1,0000

Comparison of design concepts with regards to all-weather capability:

ALL-WEATHER CAPABILITY	Ferry	Bridge	Tunnel	Decimal equivalents Ferry	Bridge	Tunnel	Normalized weights Ferry	Bridge	Tunnel	Row	Average
Ferry	1	9	5	1,0000	9,0000	5,0000	0,7627	0,8824	0,4545	2,0996	0,6999
Bridge	1 / 9	1	5	0,1111	1,0000	5,0000	0,0847	0,0980	0,4545	0,6373	0,2124
Tunnel	1 / 5	1 / 5	1	0,2000	0,2000	1,0000	0,1525	0,0196	0,0909	0,2631	0,0877
				1,3111	10,2000	11,0000					1,0000

Comparison of design concepts with regards to capacity:

CAPACITY	Ferry	Bridge	Tunnel	Decimal equivalents Ferry	Decimal equivalents Bridge	Decimal equivalents Tunnel	Normalized weights Ferry	Normalized weights Bridge	Normalized weights Tunnel	Row	Average
Ferry	1	9	3	1,0000	9,0000	3,0000	0,6923	0,5294	0,7241	1,9459	0,6486
Bridge	1 / 9	1	1 / 7	0,1111	1,0000	0,1429	0,0769	0,0588	0,0345	0,1702	0,0567
Tunnel	1 / 3	7	1	0,3333	7,0000	1,0000	0,2308	0,4118	0,2414	0,8839	0,2946
				1,4444	17,0000	4,1429					1,0000

Comparison of design concepts with regards to useful life:

				Decimal equivalents			Normalized weights			Row	Average
USEFUL LIFE	Ferry	Bridge	Tunnel	Ferry	Bridge	Tunnel	Ferry	Bridge	Tunnel		
Ferry	1	9	3	1,0000	9,0000	3,0000	0,6923	0,5294	0,7241	1,9459	0,6486
Bridge	1 / 9	1	1 / 7	0,1111	1,0000	0,1429	0,0769	0,0588	0,0345	0,1702	0,0567
Tunnel	1 / 3	7	1	0,3333	7,0000	1,0000	0,2308	0,4118	0,2414	0,8839	0,2946
				1,4444	17,0000	4,1429					1,0000

Weighted evaluation of alternatives:

0,0439*0,1932+0,1731*0,2605+0,4512*0,6999+0,1968*0,6486+0,1350*0,6486 = 0,5846

	Initial cost	Life cycle cost	All-weather capability	Capacity	Useful life	**Alternative weighted evaluation**
Criteria weights	0,0439	0,1731	0,4512	0,1968	0,1350	
Design concepts						
Ferry	0,1932	0,2605	0,6999	0,6486	0,6486	**0,5846**
Bridge	0,7235	0,6333	0,2124	0,0567	0,0567	**0,2561**
Tunnel	0,0833	0,1062	0,0877	0,2946	0,2946	**0,1594**

Based on the performed pair-wise comparisons, the ferry is the preferred design concept!

Consistency ratio

- The Consistency Ratio is an approximate mathematical indicator of the consistency of the pair-wise comparisons.

- It is a function of what is called the maximum eigenvalue and consistency index, which is then compared against similar values if the pair-wise comparisons had been merely random.

- If the ratio of consistency index to random index, known as consistency ratio, is no greater than 0,1, Saaty suggests the consistency in the comparisons is acceptable.

Consistency ratio

First the matrix of pair-wise comparisons is multiplied by the vector of normalized weights:

1,0000	0,2000	0,2000	0,3333	0,1429		0,0439		0,2537
5,0000	1,0000	0,3333	0,3333	3,0000		0,1731		1,0138
5,0000	3,0000	1,0000	9,0000	3,0000	X	0,4512	=	3,3663
3,0000	3,0000	0,1111	1,0000	3,0000		0,1968		1,3030
7,0000	0,3333	0,3333	0,3333	1,0000		0,1350		0,7162

1.0000x 0,0439 + 0,2000x0,1731+ 0,2x0,4512+ 0,3333x0,1968 + 0,1429x0,1350 = 0,02537

Consistency ratio

Next, divide each element in the obtained matrix by its corresponding value in the matrix of normalized weights:

$$\frac{0{,}2537}{0{,}0439} \quad \frac{1{,}0138}{0{,}1731} \quad \frac{3{,}3663}{0{,}4512} \quad \frac{1{,}3030}{0{,}1968} \quad \frac{0{,}7162}{0{,}1350}$$

which yields:

5,7737	5,8569	7,4610	6,6213	5,3054

Consistency ratio

Now, the average of the numbers in the obtained vector is an approximation of the so-called maximum eigenvalue:

lambda max = 6,2037

The consistency index for a matrix of size N is given by:

CI = (lambda max – N) / (N – 1)

Consistency ratio

Therefore, CI = (6,2037 – 5) / (5 – 1) = 0,3009

Random indexes for various matrix sizes were approximated by Saaty:

N	1	2	3	4	5	6	7	8	9	10	11	...
RI	0,00	0,00	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49	1,51	...

Consistency ratio

- The Consistency Ratio (CR) would then be:

  CR = CI / RI = 0,3009 / 1,12 = 0,2686

- As the obtained value is greater than 0,10 it somehow indicates potential lack of consistency in the pair-wise comparisons, that should be thus revisited!

Sensibility analysis

- What if the difference between the first ranking option and the second were smaller?

  What if reasonable changes in the values of the pair-wise comparisons would yield a different recommendation?

  .....

- Question is .... how well could we sleep after such a decision?

Further posibilities

In case of doubt after the previous what-if considerations, several options are possible:

- ✓ **talk again to the customer and better ascertain his true need**
- ✓ **identify other potential design concepts**
- ✓ **increase the number of criteria with which to discriminate the preferred option**
- ✓ **......**
- ✓ **what else? ..... there is always something more to be done or considered!!**

Design concept

- After the identification of the preferred design concept, the same process is applied iteratively to identify potential solutions for subsystems.

- For example, for the propulsion subsystem, several potential solutions are identified:

  - oars
  - diesel engine & propeller
  - steam plant & propeller
  - gas turbine & propeller
  - electric pods
  - magneto-hydrodynamic system
  - sails
  - ….